Decision making for future energy systems

Decision making for future energy systems:

Incorporating rapid change and future uncertainties

Final report

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Executive Summary

The need to achieve net-zero carbon emissions by 2050 means that Britain's energy systems must evolve rapidly so as to meet future requirements, and to cope with the considerably greater variability of renewable energy supplies. Ofgem will have a key role to play in advising government and in the planning and development of the energy infrastructure decision-making process necessary for this to happen. This will require a much higher level of communication and interaction between stakeholders, analysts and decision-makers. Further, the current fairly mechanistic decision-making processes will themselves need to be replaced by more flexible procedures in which the exercise of considerably more judgement will be required. As a consequence, more strategic control of the decision-making process will be needed. There needs to be, *inter alia*, more attention given to both the specification and development of appropriate future scenarios, and their ensuing analysis. Whether this strategic control should be exercised by Ofgem, BEIS, or elsewhere in government, probably with the advice of the Committee on Climate Change, is unclear; but it should be recognised that some decisions concerning regulation in the shorter term have the potential to constrain the UK's longer term net-zero strategy. The reliance on just four FES scenarios for planning is unlikely to illuminate all the issues relating to the UK's net-zero strategy, particularly when the development and maintenance of these scenarios is not under the direct control of Ofgem or another body with a public service remit. Moreover, the analysis relating to planning and development in the context of developing a net-zero strategy is likely to need more resource than Ofgem has used in the past.

In the report, the following issues are discussed:

- The management of uncertainty
- Scenario definition and scenario-focused decision analysis
- Robustness and sensitivity considerations
- Concerns about the use of least worse regret analyses

Recommendations

Ofgem's role in future infrastructure decision-making

In order to fulfil its future planning, development and regulatory functions within the rapid evolution of Britain's energy infrastructure, and to ensure sound, auditable decision-making, Ofgem should take more control of the analytical and decision-making processes themselves. Particularly it needs to ensure that these are correctly aligned with consumer and societal objectives. (Section 1)

Management of the analytical and decision-making processes

Serious thought should be given to the structuring and management of the analysis and decision-making processes. Ofgem should ensure that it has sufficient control of these so as to be able to ensure that they satisfy its planning, development and regulatory requirements. Analysis, including the scenarios to be used and the robustness and sensitivity analysis to be performed, needs to be agreed between decision makers and analysts in advance, and larger analysis teams are likely to be required. In particular, there needs to be provision for ongoing interaction between all the parties involved. (Sections 3.1, 3.2)

Uncertainties

At the outset of any project, uncertainties should be clearly set out and their natures determined. The methods of handling these uncertainties should be agreed. Deep uncertainties (those which may not or should not be probabilistically quantified) will require a particularly considered approach to their analysis. (Section 2.1)

Need for thorough documentation of analysis

Very clear and complete documentation should be provided of all modelling and analysis. This should include full specification of models, assumptions, scenario and decision spaces, objectives, constraints, decision-making criteria, and robustness and sensitivity analysis. The standard of documentation should be such that the analysis is fully capable of being reproduced, and the conclusions verified. (Section 3.3)

Scenario definition

Scenarios should fully reflect the range of concerns and uncertainties relevant to the decision-making problem under study. They should cover and reflect those uncertainties which may materially affect the decisions to be made within that problem. They need to be defined in consultation with, and owned by, the decision-makers. (Sections 2.2, 4.1)

Long-term planning should consider many more scenarios and sensitivities and considerably greater analysis of the robustness of conclusions against departures from these scenarios. (Sections 4.1)

A reasonable way of proceeding would be the definition of:

- a set of *core* scenarios, which should cover the likely views of the future with a high degree of confidence; each of these could be analysed in some detail, and the set of such scenarios used to identify a set of good or near "optimal" policies or decisions; these core scenarios should be *consistent* with the need to meet legally-binding carbon reduction targets;
- a further set of *non-core* or *extreme* scenarios, representing the many other less likely possible evolutions of the future -- including, particularly, things which might go wrong; these latter scenarios might be used to test the *robustness* of those decisions suggested by the core scenarios; non-core scenarios could examine the effects of failures to meet legally-binding carbon reduction targets.

There would typically be no need to analyse the non-core extreme scenarios to the same degree of detail, perhaps not even quantitatively, as required for the core scenarios. Their purpose would be to identify eventualities which need to be thought about, and thus to separate robust from non-robust decisions. (Sections 2.2, 4.1, 4.4, 4.5, 5)

Analysis

Individual scenarios should be sufficiently well specified that uncertainties within each scenario may be treated probabilistically. Probabilistically unquantifiable uncertainties should be captured by the specification of separate scenarios corresponding to each possibility. (Section 4.2)

The iterative aspects of the analytical process should be structured so that not every possible decision needs to be analysed in detail with respect to every scenario. In particular many possible decisions might be rapidly ruled out at an early stage. (Sections 2.2, 4.1)

The analytical process requires the recognition that decisions are properly made at those times at which it is optimal to do so, and thus analysis needs to be structured sequentially by identifying times at which future relevant information may become available. (Section 4.3)

Sensitivity and robustness analysis

The robustness of decisions against variations of assumptions and uncertainties, and the sensitivities of these decisions to parameter variations should all be fully tested. Graphical analyses can assist in this and consideration should be given to the provision of interactive tools to enable decision makers to carry out easily their own further explorations, e.g. Bayesian sensitivity analyses. (Sections 5.1, 5.2)

Decision-making criteria

It is our view that, especially in the context of long-term decision-making in which deep uncertainties are present, there is no simplistic or "automated" method of analysis for the management of these uncertainties so as to arrive at an optimal decision. (We are particularly concerned about the use of least worst regret analysis in this context.) Rather, as discussed in the rest of this report, judgements are required at many stages in the decision-making process. (Section 5.3)

Contents

1 Introduction

Britain's energy systems must evolve rapidly so as to meet future requirements, and to do so in way which ensures the country can meet its legally-binding carbon reduction targets – in particular that of net-zero by 2050. A consequence of the latter is that there is likely to be a much greater dependence on electricity, and that much of this may be generated from renewables. Further fundamental changes, such as a move from natural gas to hydrogen, perhaps much wider use of district heating schemes, and greater use of electric vehicles have varying degrees of likelihood, but some will happen. These will necessitate massive changes in the country's energy infrastructure, in terms of both capacity and the ability to manage a system with much increased day-to-day variability and uncertainty. To meet what may be a two to fourfold increase in demand for electricity, there will need to be an increase in capacity of the national grid and/or a much-increased emphasis on local generation.[1]

This rapid evolution of energy systems in a world in which technological change is also very rapid introduces much greater uncertainty into the infrastructure planning and decision-making processes than has hitherto been the case. This requires a more flexible and interactive approach to such decision-making than the relatively mechanistic methodologies currently used. Analysts, stakeholder and decision-makers will need to interact more closely to share understandings and develop a comprehensive agreed strategy to achieve the country's net-zero carbon ambitions. Decision-makers will need much more information on the consequences of different elements of the strategy and of varying modelling and analytical assumptions. Notably, decision-makers need to be able to understand the *robustness* of their decisions given the many uncertainties faced, where the term *robustness* is to be understood in its everyday sense of meaning that these decisions continue to be good under variations in these uncertainties and in other assumptions.

Ofgem will have a key role to play in all this in advising government on the role of regulation within long term national strategies, while regulating the country's energy systems in the shorter term so that they can be developed in line with whatever long-term net-zero carbon strategy is adopted. This is a herculean task which challenges Ofgem's current establishment and operating practices in many ways, two being particularly significant.

1. There will be a clear need for Ofgem to undertake more analysis than previously, when it was concerned solely with issues related to shorter term regulation. Its analyses rely on the *Future Energy Scenarios* (FES) developed at National Grid. As we shall discuss, this very much limits the perspectives and analyses that Ofgem can use in its regulatory function.
2. If a longer view on the path to net-zero carbon is to be taken, Ofgem, independently or with other government agencies and departments, needs to take more control of the development of scenarios and consider a much wider range of these, including broad brush ones of much lesser detail than the four FES.

In the following, we discuss our reasoning behind these assertions. We begin with a broad overview of some basic concepts and issues that arise in developing sound, auditable decisions, particularly those that address deep, long-term uncertainties (see particularly Section 3.3). We then use these to explain our – necessarily broad – advice to Ofgem on decision-making in its regulatory role and on how it should develop its longer-term advice to Government on the role of regulation in achieving the UK's net-zero carbon targets.

Some of our recommendations, if accepted, would involve considerable additional resource and so might well take time to implement. However, other recommendations – in particular, those relating to analysis and decision-making – would be capable of being acted on immediately.

2 Management of Uncertainty

2.1.1 Nature of uncertainty

We enlarge on here a distinction made in an earlier report, as to some fundamentally different types of uncertainty which need to be thought about and managed separately[2].

2.1.2 Stochastic Uncertainties

Stochastic uncertainties relate to randomness in the environment and populations and are reasonably capable of being probabilistically quantified and modelled, given a knowledge of the backgrounds against which they occur. They include such things as adverse weather conditions (severe winter or summer weather, sustained periods of no wind, flooding, etc), unusual patterns of demand, generator and network failures, and variations in populations. For varying reasons, these uncertainties are likely to be greater in the future than at present. For example, climate change will increase the variability of weather conditions, while increased renewable generation will increase the variability of supplies. Depending on how it is managed, the recharging of electric vehicles may either increase or smooth variabilities in the demand process. The management of such probabilistic uncertainties is relatively uncontroversial in principle, in that this is a matter of correctly estimating and assigning joint probability distributions. This process, however, may still present a very considerable challenge; and will need increased resource in terms of increased ongoing data collection and analysis.

2.1.3 Epistemic Uncertainties

Epistemic (or epistemological) uncertainties relate to a lack of knowledge: e.g. whether a hydrogen energy system will develop by 2030 with, say, 20% of transport and 10% of domestic heating so fuelled. Uncertainties about the values of parameters in a model are also epistemic; as, indeed, is any uncertainty about the appropriateness of the model to use in a particular context. Such uncertainties are not stochastic, but they can be modelled probabilistically if a Bayesian[3] perspective on probability is taken. Computational advances and many applications having shown over recent decades that Bayesian ideas are feasible, efficient and in tune with decision makers' needs. However, there are some issues when epistemic uncertainties are *deep*[4]. Uncertainties are deep when there is little agreement between all parties to a decision (decision makers, stakeholders, experts) on the appropriate models to use and the probability distributions to use to describe the uncertainties on key parameters. Moreover, deep uncertainties are characterised by the need to make a decision before the disagreements over the uncertainties can be resolved.

2.1.4 Social, Economic and Political Uncertainties

These are many uncertainties that are simply not capable of being objectively quantified – whether probabilistically or in any other way – but whose relative plausibilities need nevertheless to be considered. These also include uncertainties that it would be inappropriate to attempt to quantify, in that this would involve, for example, the second-guessing of government or other public policy. Many involve significant ambiguities that can only be resolved by discussion and deliberation. Such uncertainties may also be deep in that they may be very significant disagreements between the parties to the decision.

2.2 Uncertainties and scenarios

Complex decisions dealing with outcomes that stretch years or decades into the future inevitably involve many deep uncertainties. Our knowledge of what events may happen and affect outcomes many years from now is far from complete. Moreover, in many cases we may not be entirely clear about how we will value outcomes when they happen, simply because we have not imagined the situation. For instance, the coronavirus lockdown has changed many people's and employers' views on home working and their preferences may well be different to what they would have said only a few months ago – less dramatic examples would include the development of entirely new technologies, or recent instances of very rapid price reductions of existing technologies such as solar power and offshore wind power.

One of the ways that analysts can help in exploring decisions in face of deep uncertainties is to explore several scenarios[5]. Scenarios may be developed in which:

- Some key deep uncertainties are fixed at 'interesting' values. Interesting values may be identified in many ways:
  - outcomes that decision makers and/or stakeholders find particularly worrying or attractive, i.e. reasonable worst or best cases;
  - a best guess scenario, i.e. if things go as much as planned;
  - outcomes that would follow if some dramatic, but unlikely event happened, e.g. a further pandemic or the advent of fusion energy.
- It is also valuable to create scenarios which capture specific value/cultural perspectives and thus capture the perspectives of particular groups of stakeholders.

Note that although such scenarios look like events on which probabilities may be defined, it is in general impossible to choose sufficient scenarios as to completely span or partition the future. Thus even a Bayesian analysis in which probabilities are formally assigned to scenarios to permit some form of averaging is problematic. (See, however, Section 5.2 where we explore the idea of using *flexible* Bayesian analyses as part of a robustness analysis.)

Within each scenario, i.e. using the assumptions embodied in that scenario, it is possible to build full probability and decision models to explore how different strategies may play out. The idea of such scenario-focused decision analyses is to provide information to the decision makers and make them aware of the potential upsides and downsides of different strategies. Attractive strategies will be those which perform well across all (or most) of the scenarios, although perhaps not optimally in any of them. Such strategies exhibit *robustness*.

Such analyses will only have value to the decision-makers and their advisors *if the range of scenarios capture their concerns.* It is important, therefore, that they are fully involved in the definition and construction of the scenarios: the decision-makers and their advisors need to *own* them. Note that it is not necessary to define all the scenarios to the same level or detail. Some may be very helpful, even if only roughly drawn, in identifying weaknesses or strengths of different strategies. Thus some – perhaps many – strategies may be eliminated without detailed and expensive full analysis.

3 Decision-Making Processes

3.1 Management of decision-making processes

The process of decision-making can be divided in three broad phases though that is not to suggest that the process is linear[6]. Generally the process iterates within and between phases as one's thinking about one issue catalyses further thoughts about other issues, or reflections during one phase indicate that other issues should have been considered in an earlier one. See Figure 1.

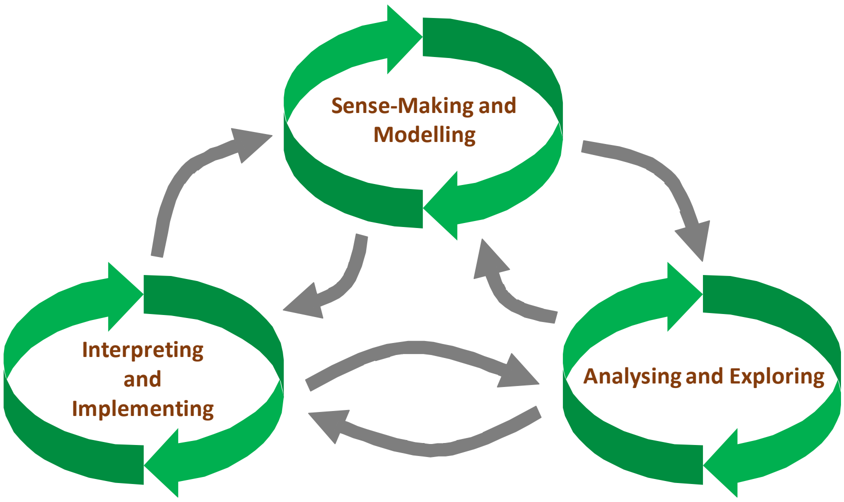

Figure 1: The Decision Analysis Process

Note: the process is seldom linear. Rather it iterates back and forward both within the three stages and between them as insights build and omissions in the model and analysis are recognised.

- *Sense-making and Modelling*. The first step in any decision is a sense-making process of identifying issues, objectives, stakeholders, possible actions and their consequences, etc. Once they are identified, stakeholders may be invited to join the process to ensure that issues that matter to them are addressed. The process also determines the scope and boundaries of the subsequent analyses. Only at this stage is it possible to build a quantitative model.
- *Analysing and Exploring*. Once a model is built, it needs to be explored and analysed in relation to the study's objectives, building understanding. Sensitivity and robustness analyses may – *should* – supplement the decision analysis, setting bounds on some of the residual uncertainty. During the process, the model should be validated as much as possible against available data and the decision-makers and stakeholders' perceptions.
- *Interpreting and Implementing*. The results and guidance offered by the analysis need to be interpreted into real world actions. This requires that the decision-makers and analysts make a judgement whether the analysis is *requisite* for the decision, guiding them to a consensus on the way forward. They need to judge whether the model, the analysis and the conclusions are fit for their purposes. They will also need to communicate the decision to stakeholders and implement the actions.

In the case of more operational, regular decisions, the first sense-making phase is less important because the relevant issues will be very similar to last time. For

Ofgem, although one would not like to suggest that its planning, development and regulatory decisions are entirely of the same structure as last time, there are many similarities.

This is not the same case as that for thinking through its position on the move to net-zero carbon systems, which requires entirely fresh analysis and deliberation. For such long-term, complex decisions, the initial sense-making and modelling phase is particularly important to ensure that all relevant issues are included in the analysis and subsequent deliberation. During this phase, there will be a need to include the views of many stakeholders within government, the energy industries, consumers and the public. This means that there will be a need for several or perhaps many workshops to explore and capture their views, agreeing on the issues to be included and those that can be omitted. Later in the decision process, there will be less need for workshops or other face-to-face interactions. But there will be a need for ongoing communication.

3.2 Decision-making and Analysis

The need to meet societal objectives will probably mean that a more strategic and coordinated management of the entire decision-making process will be required.

The first point to consider is the size of the analysis and how much of the analysis needs to be done in house if Ofgem is to both fulfil its various functions and also advise government on how these functions may need to change to guide the UK's energy systems towards net-zero carbon in line with the government's agenda. At present, Ofgem addresses its planning, development and regulatory functions by drawing on the four National Grid FES scenarios. However these scenarios are only just beginning to recognize the major infrastructure changes that will be required by the move to net-zero carbon, and from the FES documentation it is unclear to what extent the scenarios have been developed with the purpose of network planning in mind. They will therefore require much further, and quite urgent, development. Further, such are the future uncertainties, that a larger number of scenarios will need to be considered, and this number will necessarily increase in the case of longer-term decision-making.

Successful modelling and analysis requires a combination of skills, including, in this case, detailed energy systems knowledge along with the mathematical and statistical skills required to manage the many uncertainties involved. For the modelling necessary for thinking about future energy systems and infrastructure, and for the reasons discussed in Section 3.1, almost certainly a larger group of analysts – including representatives of Ofgem – are needed than are at present used. These analysts need to talk to the decision-makers both before and during the analytical process, so as to identify the primary objective(s) of interest, and agree a detailed approach. This process needs to include the formal identification of key uncertainties and the explicit identification of how these will be investigated. In particular, decision makers and analysts need to ensure that the scenarios used to support the deliberations allow exploration of all Ofgem's concerns. Appropriate robustness and sensitivity analyses need to be agreed. Ideally, there should be ongoing discussion between analysts and decision makers, again as discussed in Section 3.1; at a minimum, there should be a good reporting process in place -- see Section 3.3.

Overall our view is that, in order to fulfil its likely future obligations in ensuring that the evolution of energy infrastructure is compatible with the transition to net-zero carbon emissions, it will be essential that Ofgem, BEIS and other government agencies have more broad strategic control of the evolution of the entire decision-making process because it will shape the early stages of the UK's net-zero strategy.

3.3 Documentation of Analyses

Continual iterative discussion between decision-makers, stakeholders, scientific and economic experts and analysts can be very difficult under the current division of responsibilities, since these groups of people often belong to different organisations and are seldom co-located. Moreover, there is a continual changeover of personnel across Government departments and agencies and within the energy companies concerned. This situation greatly increases the need for very thorough documentation of analysis, including the basis of assumptions built into the modelling. Clear documentation provides an audit trail and the reasoning behind the decision which is often needed during the implementation phase for clarification of some issues. Documentation need to be transparent, therefore, ideally to the same standards of transparency as in the case of a scientific paper submitted for peer-review, and the analytic results should be capable, if necessary, of being checked and reproduced.

In particular, within the documentation, and for the reasons discussed elsewhere in this report, there need to be precise definitions and specifications of:

- models,
- variables and relationships between them,
- assumptions and parameter values,
- scenario space,
- decision space,
- constraints (e.g. security-of-supply, carbon reduction targets),
- decision-making criteria (e.g. the minimisation of an expected economic cost, or of a worst regret, or the maximisation of an NPV, in all cases subject to meeting the specified constraints),
- robustness analysis.

4 Scenario definition and analysis

4.1 Scenario definition

It is important that scenarios provide sufficient coverage of possible futures, including (particularly) unforeseen eventualities (e.g. unavailable nuclear power or other technologies, non-availability of energy supplies - gas or electricity - from abroad). When infrastructure or other decisions have consequences lasting well into the future, then the scenarios used for the corresponding decision-making process need to run at least that far into the future and to cover sufficiently the range of possibilities throughout the entire time period concerned. This has a number of important consequences:

1. the scenarios to be considered are particular to the problem at hand and reflect those uncertainties which may materially affect the decisions to be made within that problem;
2. long-term planning, e.g. of network infrastructure, involves many more and very much greater uncertainties, than short-term decision-making. e.g. provision of margin; in consequence long-term planning requires the consideration of many more scenarios and sensitivities and considerably greater robustness analysis;
3. similarly long-term planning involves deep uncertainties which cannot simply be treated by routine analytical procedures.

It seems that at present the Future Energy Scenarios (FES) developed by National Grid are used for almost all aspects of decision-making throughout the industry and over all time periods. However, there are currently only *four* FES. While these may provide sufficient coverage for some short-term decision-making – such as that associated with capacity adequacy and the capacity markets, where one is not looking more than a few years into the future and the scenario and decision spaces are essentially one-dimensional – they seem quite inadequate in providing the coverage required for infrastructure decision-making where the consequences of particular decisions persist for maybe 40 or more years. Moreover, it is important to note that the FES were not developed to support regulatory decisions alone, or even with that as their primary purpose. National Grid needs such scenarios for its internal planning, as does the rest of the industry. It is possible, therefore, that they may not sufficiently cover those uncertainties which are relevant to regulatory and other societal interests for which Ofgem has responsibility.

Thus, our view is that, for planning further ahead than a very small number of years, many more scenarios are needed to provide adequate coverage of future possibilities and eventualities, though as noted some scenarios may be developed in more detail than others. One might reasonably proceed by defining[7]:

- a set of *core* scenarios, which should cover the likely views of the future with a high degree of confidence; each of these could be analysed in some detail, and the set of such scenarios used to identify a set of good or near "optimal" policies or decisions;
- a further set of *non-core* or *extreme* scenarios (or sensitivities), representing the many other, but less likely, possible evolutions of the future -- including, particularly, things which might go wrong (as suggested above); these latter scenarios might be used to test the *robustness* of those decisions suggested by the core scenarios; there would typically be no need to specify, analyse or cost these extreme scenarios to the same degree of detail as required for the core scenarios. Their purpose would be to identify eventualities which needed to be thought about, and thus to separate robust from non-robust decisions.

With regard to the feasibility of analysing more scenarios than at present, it needs to be remembered (a) that very much more computing power has become available in recent years and also that thoughtful analytical approaches – or even better computer coding – can often greatly reduce the volume of computation required, (b) as suggested above, not every scenario or sensitivity needs to be analysed in fine detail.

4.2 Analysis

As is implicit in the foregoing discussion, analysis is almost inevitably based on the consideration of scenarios, and on the interactions between scenarios and possible decisions.

We believe that individual scenarios should be sufficiently well specified that uncertainties within each scenario may be treated probabilistically. Thus all probabilistically unquantifiable uncertainties – corresponding to, e.g., possible political or economic directions, or to possible extreme events – need to be captured in the specification of separate scenarios corresponding to each possibility. Anything else, involving unquantifiable uncertainties both within and between scenarios, is almost certain to lead to an analytically intractable situation. (See also the discussion Section 4.3.)

4.3 Treatment of time

Since uncertainty is something which evolves over time, this needs to be taken account of within any analysis. In particular, decisions need to be made at those times at which it is optimal to do so, and thus analysis needs to be structured by identifying times at which future relevant information may become available.

A very simple example is given by considering an infrastructure decision in which there are three possibilities: (a) build immediately, (b) build in 1 year's time, (c) never build. If more information is to become available in a year's time, then the only immediate decision required is whether to (a) build immediately, (b) postpone any decision for 1 year. Within a probabilistic environment, this involves comparing the cost (or perhaps NPV[8]) of building now, with the expected total cost under a year's postponement. (An elementary probabilistic inequality shows that the latter will always be less than would be the case if the further decision were to be made immediately.) Hence, in this particular example, the decision space for the immediate problem is binary.

Again within a probabilistic environment, the same philosophy may be extended to multiple future decision points – formally the analysis is that of stochastic dynamic programming.

A (rare) special case occurs when, within a scenario, no further information becomes available as time progresses. In this case one may assume that all decisions within that scenario may be made immediately. (This is effectively what happens within current analyses for determining procurement within the GB Capacity Market, where the optimal procurement for the 4-year ahead market is made, without the analysis being able to take any account of the possibility of an adjustment in the 1-year ahead market.)

However, there is no entirely consistent analytical way to handle the evolution of uncertainty over time outside of a probabilistic treatment. This reinforces the earlier recommendation to deal with non-probabilistically quantifiable uncertainties through a process of informed judgement based on the definition of separate scenarios.

4.4 Analysis of multiple scenarios

The difficulties of combining multiple scenarios in decision-making are well known: on the one hand, the relative likelihoods of these scenarios obviously matter, and in particular, very unlikely scenarios need to be identified as such. On the other hand, since the scenarios have not been defined to form a mutually exclusive partition of the possible futures, it may be extremely difficult or conceptually impossible to assign probabilities to scenarios[9].

One way of proceeding might be as suggested in Section 4.1, via the identification of a set of core scenarios which might be regarded as a representative set of "equi-plausible" evolutions of the future and which could be analysed in detail, (with plenty of robustness analysis), to obtain a set of good – or close to optimal – possible decisions. In addition, one would define (again as suggested earlier) a set of non-core or extreme scenarios, which would include all unfortunate eventualities, which would not need to be analysed in such great detail, and which could be used to further test the robustness of possible decisions. See also the further discussion of Section 5.

4.5 Need to respect legally-binding carbon reduction targets

This is of course a major issue, which – where relevant - should properly place constraints on any analysis. One possibility, if one proceeds as suggested above via the definition of "core" and "non-core" scenarios, is that the former should all be compliant with meeting these legally-binding targets (so that primary analysis does not attempt some even-handed compromise between meeting and not meeting them). It is, however, necessary to explore what happens if these legally-binding targets are for some reason not met. This might be done through the definition of appropriate non-core scenarios, whose consequences could be thus explored[10].

5 Sensitivity and robustness analysis

5.1 Sensitivity analysis for parameters

There is a need to provide information on the *sensitivity*, or *robustness*, of decisions to individual parameter assumptions[11]. In general, this would most sensibly be done graphically, e.g. with plots of how suggested decisions might change as parameters were varied. This could then be used to suggest decisions which are robust against parameter variation.

It is further necessary to understand -- either analytically or through experimentation -- how parameter assumptions interact with each other. Again results might be presented with appropriate graphical analyses.

5.2 Sensitivity to relative likelihoods of scenarios

For the reasons discussed in Section 2, it is not desirable that one should assign a single set of probabilities to the various scenarios considered. Nevertheless, again as mentioned earlier, the relative likelihoods of scenarios do need to be taken into consideration. It might therefore make sense to provide interactive tools to enable *decision-makers* to perform their own Bayesian sensitivity analysis by exploring the consequences of assigning varying probabilities[12] to scenarios and looking at how the optimal decision under a Bayesian analysis would then vary.

This generalises the idea – found for example within the NOA analysis – of calculating *switching probabilities*, so as to examine the effect of varying the relative likelihoods of just two scenarios.

However, there is one further problem we should mention here. Within scenarios, a full Bayesian analysis will produce a ranking of options based upon the ordering of expected utilities. However, the utilities within scenarios are not *necessarily* comparable numerically across scenarios[13]. This will require that care is taken to check that no scenario represents such a dramatic change from the present that it is unreasonable to expect that the government's and society's values remain the same.

5.3 Least worst regret (LWR) analysis and weighting of scenarios

LWR analysis is often proposed as a way of comparing the outcomes of scenarios across different strategies. A claimed advantage of such analysis is that it does not require consideration to be made of the relative likelihoods or plausibilities of the scenarios considered, so that LWR analysis is often regarded as "objective". However, we are very uncomfortable with this. First, the outcome of an LWR analysis is determined entirely by the set of scenarios chosen for inclusion in the analysis, and indeed is usually almost entirely determined by a very small number of “critical” scenarios that are in some way (which can be made mathematically precise) extreme.[14] However, the *choice* of scenarios to be included in an analysis is *not* an objective one, and indeed the choice of the more extreme scenarios which are critical to the outcome of the analysis may be made by analysts who are quite remote from the decision owner without the necessary statement of purpose to guide the scenario specification, or through a perceived need to sufficiently populate the scenario space.[15] Further, this small number of critical scenarios may not reflect all the risks that are represented across all scenarios. During implementation of a LWR strategy, such risks may be forgotten. Finally, if the critical scenarios that determine the outcome of LWR analysis are particularly optimistic or pessimistic about the future, it may lead to a decision that performs poorly in the circumstances that actually occur.

LWR analysis also assumes that all preferences are comparable across scenarios and this, as we have suggested, may be an unreasonable assumption in some circumstances, particular when facing long-term futures during which there may be dramatic changes to society.

As mentioned above, LWR analysis simply takes no account of beliefs as to relative likelihoods of scenarios, however informal these may be[16]. Yet such beliefs matter and need to be formally or informally incorporated within any analysis. Frequently this is implicitly done within the choice of scenario set itself.

It is our view that, especially in the context of long-term decision-making in which deep uncertainties are present, there is no “automated” method of analysis for the management of these uncertainties so as to arrive at an optimal decision. Rather, it is necessary to proceed as we have outlined in the rest of this report – see, especially, Section 4 – so that, inevitably, judgements are required at many stages in the decision-making process.

5.4 Unmodelled considerations and constraints

There are also important considerations whose incorporation within a formal modelling and analysis process may unduly complicate the latter. Typically, these will be practical constraints: e.g., where the preferred outcome suggested by an analysis is nevertheless not manageable in practice, perhaps because it would require too many changes to be made at once.

Again a reasonable approach is to let the more formal analysis suggest a range of "good", or near-optimal, options, and to test the robustness of these against these further unmodelled considerations.

5.5 Management of multiple objectives

Bayesian approaches deal with multiple objectives by the use of multi-attribute value and utility functions[17]. These allow for trade-offs between different objectives including varying marginal value along each objective. Risk attitude is also modelled. However, since the key issue faced by Ofgem relates to how it addresses uncertainties in its planning, development and regulatory roles and its formulating its perspective and advice on policies for moving the UK energy system towards Net-Zero Carbon, we do not discuss multiple objectives in detail here.

6 Robust decision-making (RDM) approach

An apparently somewhat different approach to decision-making – originating largely from within the Rand Corporation – has been advocated in recent years by various authors[18]. This approach is usually referred to as *robust decision making* (RDM), and focuses on the early identification of robust strategies, i.e. those likely to perform well across a wide variety of possible evolutions of the future. These are then explored in further detail.

The distinction between RDM and more traditional approaches is, to a large extent, a matter of emphasis. In all cases we have (explicitly or implicitly) a scenario space (set of possible evolutions of the external environment) and a decision space. Associated with each possible scenario and each possible decision is a future evolution and a cost. Again in all cases, the objective is to find a decision which works well across multiple scenarios.

The RDM approach both permits more flexible, and perhaps more efficient, navigation towards a good decision. In particular many decisions can be ruled out at an early stage without being evaluated in detail under every scenario, as they perform sufficiently badly under at least some circumstances. The approach also helps to identify possibilities (within the, possibly very broad, scenario space) which might not have been thought about in advance.

It therefore seems to us that the benefits of the explicit RDM approach are primarily those of efficiency within the decision-making process. However, the RDM approach requires a very high level of interaction between analysts and decision-makers, and this is not easy when the two groups belong to separate organisations. The approach is something towards which Ofgem might well work in the future. In the absence of this, what is important is that there exists the kind of cooperation between analysts and decision-makers which we have discussed in this report, and, most especially, that analysts provide the decision-makers with the right tools to perform their own flexible analyses.

7 Recommendations and Conclusion

Drawing out discussion together we would make the following recommendations

Ofgem's role in future infrastructure decision-making

In order to fulfil its future planning, development and regulatory functions within the rapid evolution of Britain's energy infrastructure, and to ensure sound, auditable decision-making, Ofgem should take more control of the analytical and decision-making processes themselves. Particularly it needs to ensure that these are correctly aligned with consumer and societal objectives. (Section 1)

Management of the analytical and decision-making processes

Serious thought should be given to the structuring and management of the analysis and decision-making processes. Ofgem should ensure that it has sufficient control of these so as to be able to ensure that they satisfy its planning, development and regulatory requirements. Analysis, including the scenarios to be used and the robustness and sensitivity analysis to be performed, needs to be agreed between decision makers and analysts in advance, and larger analysis teams are likely to be required. In particular, there needs to be provision for ongoing interaction between all the parties involved. (Sections 3.1, 3.2)

Uncertainties

At the outset of any project, uncertainties should be clearly set out and their natures determined.   The methods of handling these uncertainties should be agreed. Deep uncertainties (those which may not or should not be probabilistically quantified) will require a particularly considered approach to their analysis. (Section 2.1)

Need for thorough documentation of analysis

Very clear and complete documentation should be provided of all modelling and analysis. This should include full specification of models, assumptions, scenario and decision spaces, objectives, constraints, decision-making criteria, and robustness and sensitivity analysis. The standard of documentation should be such that the analysis is fully capable of being reproduced, and the conclusions verified. (Section 3.3)

Scenario definition

Scenarios should fully reflect the range of concerns and uncertainties relevant to the decision-making problem under study. They should cover and reflect those uncertainties which may materially affect the decisions to be made within that problem. They need to be defined in consultation with, and owned by, the decision-makers. (Sections 2.2, 4.1)

Long-term planning should consider many more scenarios and sensitivities and considerably greater analysis of the robustness of conclusions against departures from these scenarios. (Sections 4.1)

A reasonable way of proceeding would be the definition of:

- a set of *core* scenarios, which should cover the likely views of the future with a high degree of confidence; each of these could be analysed in some detail, and the set of such scenarios used to identify a set of good or near "optimal" policies or decisions; these core scenarios should be *consistent* with the need to meet legally-binding carbon reduction targets;
- a further set of *non-core* or *extreme* scenarios, representing the many other less likely possible evolutions of the future -- including, particularly, things which might go wrong; these latter scenarios might be used to test the *robustness* of those decisions suggested by the core scenarios; non-core scenarios could examine the effects of failures to meet legally-binding carbon reduction targets.

There would typically be no need to analyse the non-core extreme scenarios to the same degree of detail, perhaps not even quantitatively, as required for the core scenarios. Their purpose would be to identify eventualities which need to be thought about, and thus to separate robust from non-robust decisions. (Sections 2.2, 4.1, 4.4, 4.5, 5)

Analysis

Individual scenarios should be sufficiently well specified that uncertainties within each scenario may be treated probabilistically. Probabilistically unquantifiable uncertainties should be captured by the specification of separate scenarios corresponding to each possibility. (Section 4.2)

The iterative aspects of the analytical process should be structured so that not every possible decision needs to be analysed in detail with respect to every scenario. In particular many possible decisions might be rapidly ruled out at an early stage. (Sections 2.2, 4.1)

The analytical process requires the recognition that decisions are properly made at those times at which it is optimal to do so, and thus analysis needs to be structured sequentially by identifying times at which future relevant information may become available. (Section 4.3)

Sensitivity and robustness analysis

The robustness of decisions against variations of assumptions and uncertainties, and the sensitivities of these decisions to parameter variations should all be fully tested. Graphical analyses can assist in this and consideration should be given to the provision of interactive tools to enable decision makers to carry out easily their own further explorations, e.g. Bayesian sensitivity analyses. (Sections 5.1, 5.2)

Decision-making criteria

It is our view that, especially in the context of long-term decision-making in which deep uncertainties are present, there is no simplistic or "automated" method of analysis for the management of these uncertainties so as to arrive at an optimal decision. (We are particularly concerned about the use of least worst regret analysis in this context.) Rather, as discussed in the rest of this report, judgements are required at many stages in the decision-making process. (Section 5.3)

In summary, we have considerable concerns about the current approach to developing regulation, particularly in relation to the overreliance on the four FES scenarios. Moreover, we do not see how the current process can extend to address much longer term decision making on the move to net-zero carbon over the coming decades. We are aware that the availability of analytic effort within Ofgem is limited, with staff already working to capacity. Thus in the short term, we recognise that the planning for next regulation round must necessarily continue along the lines used previously, though some additional guidance within current frameworks may be possible. In any case, the energy industry is expecting that and any radical change to the process might be resisted. However, we do recommend that Ofgem, perhaps with other stakeholders across Government, should consider running one or more workshops to develop several further qualitative scenarios which would complement the FES ones in the sense of including potential events and changes that are not represented within the FES scope. Options and policies for regulation could then be considered for robustness against these further scenarios. We would expect this process to be one of largely qualitative discussion in the standard manner of scenario planning adopted across much business and government.

In relation to longer-term planning, we would recommend that Ofgem urgently signals the need to BEIS and other relevant government bodies that the move to net-zero carbon and Government targets mean that the current approach to the planning, development and regulation processes may very well not be fit for purpose in the future. Extra resource needs to allocated now for developing those processes and signals sent to the energy industry that future regulation rounds may need to be very different.

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Endnotes

1 See UK Committee on Climate Change. (May 2019).

2 There are many typologies of uncertainty, each emphasizing some character or potential use of the concept, e.g. French (1995), Ganger Morgan and Henrion (1990). The three given here are sufficient for this discussion.

3 The Bayesian approach applies across statistical, risk and decision analysis and is described, discussed and justified in, e.g,, Bedford and Cooke (2001), French and Rios Insua (2000), French et al (2009), Singpurwalla (2006), Smith (2010) and Turkman et al (2019). In our view, the Bayesian approach provides the most appropriate methodology for Ofgem to follow. It has been justified and validated in many ways. It:

(i) provides the most comprehensive approach dealing with uncertainty and value judgements in very sophisticated models;

(ii) provides compatible and coherent techniques of statistical, risk and decision analysis;

(iii) is based on a well-established and explicit set of principles of rationality;

(iv) can draw in evidence both in the forms of hard data and expert judgement;

(v) allows simpler, compatible sub-models to be used to focus on specific issues;

(vi) is based on considerable experience of use in applications

4 Recent discussions of deep uncertainties are provided in French (2020), Marchau et al (2019).

5 It should be noted that 'scenario' is a word that is used in several different ways across policy and decision analysis, and that this is certainly true in energy policy analysis Hughes (2009), Hughes and Strachan (2010). In this note, we use 'scenario' in two compatible ways. Firstly, the FES scenarios (http://fes.nationalgrid.com/) developed and maintained by National Grid in which sufficiently detailed assumptions are made about future supply and demand as well as the UK energy infrastructures to be able to make quantitative forecasts about the behaviour of the UK energy system. Secondly, we suggest the use of much less detailed, more qualitative scenarios which can be used as a backdrop to strategic discussions about the robustness of possible policies: cf. van der Heijden (1996)

6 Note that there are many discussions and representations of the modelling process (Tomlinson and Kiss 2013). Figure 1 emphasises the interactive nature of the process and simplifies many specific parts of the process into three broad stages (Holtzman, 1989).

7 See Endnote 5

8 Note that NPV needs to be handled with considerable care over long time horizons, as it gives a limited view of the consequences of uncertainty and may discount future costs too emphatically.

9 Scenarios may overlap, i.e. share some assumptions, and almost certainly do not span all possible eventualities. In thinking about futures some decades away this is particularly true, in 1990, 30 years ago, the web was literally in its infancy, barely imagined and implemented at CERN. Few outside the realm of science fiction, imagined how it would underpin all facets our society today. We cannot assume that scenarios that depict possible paths to Net Zero Carbon in 2050 will cover all possible evolutions. French (2020) surveys the literature and discusses what can be assumed by looking at scenarios in the face of such deep uncertainty and what may not.

10 Note that two of the four FES scenarios are not compliant with the legally-binding targets. While such is sensible in terms of risk management, it may be less sensible in terms of setting policy to achieve the targets.

[11] French (2003) discusses sensitivity analysis in the context of risk and decision analysis. More detailed discussion of sensitivity techniques may be found in Rios Insua (1990), Saltelli et al (2000).

[12] One might think of these not as formal probabilities but *importance weights* which reflect how much influence the decision-makers wish to ascribe to particular scenarios. These weight would reflect not just likelihood, but other factors such as the need of showing that some extreme but highly unlikely risk has been taken into account (Stewart et al, 2013). Whatever the case, the process would form a weighted average across scenarios of the expected utilities used to rank options within scenarios. Obviously, there should be many sensitivity analyses of the informal probabilities/importance weights used and, arguably, as much attention paid to the robustness of policies across scenarios as to any ranking produced by a weighted average of some utility measure across scenarios.

[13] See French (2020). Essentially, with very few exceptions values are measured on interval not ratio scales. Like Fahrenheit, Celius, Reamur and other temperature scales, they need a zero and unit to be defined. The problem is that these zeros and units may differ across scenario because values can change dramatically if a scenario posits a radical change in society and the environment. We mention elsewhere that the Covid-19 crisis is causing substantial reappraisal of individuals', society's and governments' values. So before expected utilities or other value scores may be compared across scenarios, checks on the compatibility of scales must be undertaken.

[14] See Zachary (2016)

[15] It seems to be sometimes, quite mistakenly, assumed that the decision space within an analysis should consist only of those decisions each of which is optimal for some scenario (whereas in reality the best available decision may be good for most scenarios but not strictly optimal for any). This may lead to the creation of scenarios for no other purpose than to create a sufficiently rich decision space.

[16] LWR is only one of several simple – one might say naïve – decision criteria that have been proposed: e.g. Laplace's criterion, Hurwicz-α, Savage's Minimax Regret. All have flaws (see, e.g., Luce and Raifa, 1957; French 1986). Moreover, with the exception of LWR and Laplace's equiprobable weighting, there have been very few applications of any in practice. They survive solely perhaps in that they allow simple exercises to be given to students in elementary OR courses! It should also be noted that LWR and Laplace's equiprobable weighting are *not* equivalent as is sometimes quite falsely stated.

[17] See e.g. French et al (2009), Keeney (1992), and Keeney and Raiffa (1993). Gregory et al (2013) discuss how such methods may be used to articulate discussion about objectives between different stakeholders. Note that while Bayesian approaches use multi-attribute value and utility models to address multiple objectives, there are many other approaches known under the collective heading of multi-criteria decision analysis (MCDA): see Belton and Stewart (2002). Some of these methods are compatible with Bayesian approaches, indeed Bayesian methods are often categorized as MCDA. However, some other methods lack such firm foundations.

[18] Robust decision-making (RDM) and deep uncertainty are intimately connected in current developments: see Marchau et al (2019). Much of this literature stems from approaches developed at the Rand Corporation over several decades. Some RDM approaches are essentially Bayesian, but others are not. For instance, *Least Worst Analysis* may seem sensible, but it focuses attention on one aspect of one scenario, and may miss poor performance on more important aspects of other scenarios. In our report we take a Bayesian view on RDM and also focus on its process aspects.

Note also that 'robust' is another word with multiple uses across areas of decision analysis. As we use it in this report, we mean that a strategy is robust if it performs reasonably well across all foreseen scenarios.